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STUDY OF OCEANIC LITHOSPHERE USING GEOS-3 RADAR ALTIMETER DATA.(U)
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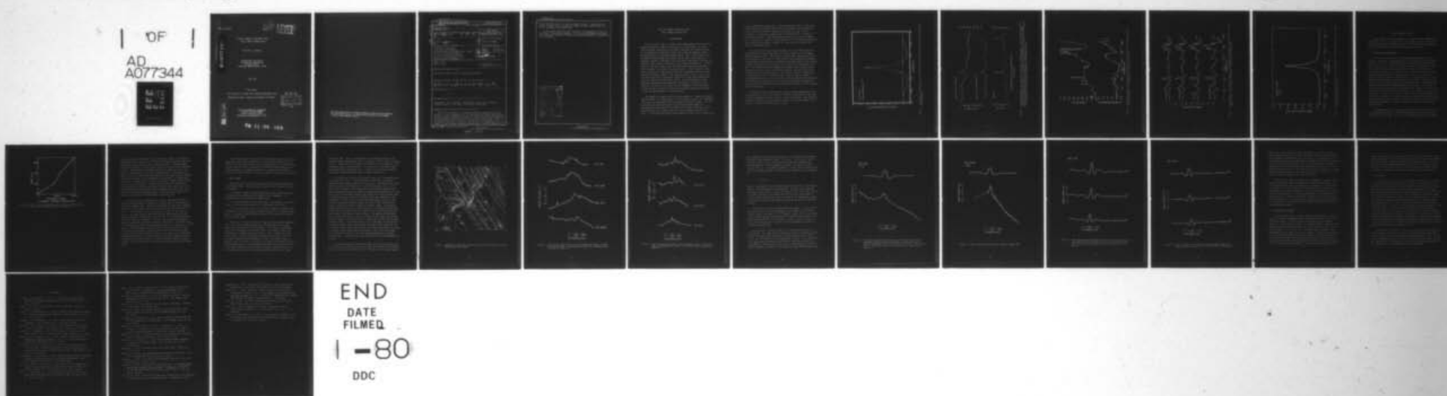

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STUDY OF OCEANIC LITHOSPHERE USING GEOS-3 RADAR ALTIMETER DATA

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July 1979

Final Report

For the period 1 October 1977 through 30 September 1979

Approved for public release; distribution unlimited.

AIR FORCE GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
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19 **REPORT DOCUMENTATION PAGE**

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: 18 AFGL-TR-79-0181	2. GOVT ACCESSION NO.
	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): 6 STUDY OF OCEANIC LITHOSPHERE USING GEOS-3 RADAR ALTIMETER DATA.	5. TYPE OF REPORT & PERIOD COVERED: Final Report For the period 1 October 1977 through 30 September 1979
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): 10 Micheline C. Roufosse	8. CONTRACT OR GRANT NUMBER(s): 15 F19628-78-C-0003
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Smithsonian Institution Astrophysical Observatory 60 Garden Street, Cambridge, Mass. 02138	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 61102F 16 2309G1AQ 17 G1
11. CONTROLLING OFFICE NAME AND ADDRESS: Air Force Geophysics Laboratory Hanscom AFB, Massachusetts 01731 Monitor/Thomas P. Rooney/LWG	12. REPORT DATE: 11 Jul[redacted]79
	13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): 12 30	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (*of this Report*)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)

9 Final rept. 1 Oct 77-30 Sep 79,

18. SUPPLEMENTARY NOTES

044 850

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

lithosphere - time evolution - geoid heights - Geos 3 radar altimeter - flexural rigidity - Airy model - thin-elastic-plate model

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

The aim of this work is to study the mechanical properties and time evolution of the lithosphere. For that purpose, geoid heights derived from the Geos 3 radar altimeter were used. The study of the correlation existing between bathymetry and free-air anomalies or geoid heights gives information on the mechanical properties of the lithosphere and its thickness. The lithospheric thickness is related to the age of the lithospheric plate, and by probing several locations spanning varied temporal situations, ~~we are~~ one is able to cont'

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retrace the time evolution of the lithospheric plates. Toward that aim, several seamount chains, islands, and ridges have been investigated in the Pacific, Atlantic, and Indian Oceans.

In the regions studied so far, the age of the lithosphere at the time of loading is the primary parameter. In this work, ~~we~~ the author attempts a systematic study of all the parameters influencing the observed mechanical properties of the lithosphere.

STUDY OF OCEANIC LITHOSPHERE USING
GEOS-3 RADAR ALTIMETER DATA

1. INTRODUCTION

The aim of this study is to gain a better understanding of the structure, mechanical properties, and time evolution of the lithosphere. By using a simplified model, the behavior of an ideal lithosphere as a function of age can be theoretically predicted (Crough, 1975; Crough and Thompson, 1976a), but that method can provide only general trends. While local studies can be performed by using surface ship gravity data and their correlation with bathymetry (Walcott, 1976; Watts, 1976, 1978; Watts and Cochran, 1974; Detrick and Watts, 1979), these are necessarily very limited geographically. We have chosen in this work to make use of the geoid heights provided by the Geos 3 radar altimeter, which covers all oceanic regions. Since the oceanic lithosphere is simpler to study than the continental lithosphere, we have limited our effort to oceanic regions. Our intent has been to select as many sites as possible that offer a good geoid signal and to study them systematically, hoping to obtain a good statistical sample. The geoid heights were then inspected, together with the bathymetry, the magnetic lineations, the age, formation, and history of the load, and the lithospheric age and evolution. Our goal has been to establish positive relationships among these parameters so as to use geoid heights as a predictive tool.

Our method, fully described in Scientific Report No. 1 under this contract (AFGL-TR-78-0271), is summarized here. We limited our study to the interpretation of the short-wavelength signals contained in the geoid heights. In order to separate the short-wavelength from the long-wavelength components, a reference geoid calculated with the GEM10 or SE IV spherical-harmonics expansion coefficients up to degree and order 16 was subtracted from the total field. In most cases that method proved adequate, except in areas characterized by poor surface-data coverage such as the South Atlantic Ocean off the coast of South Africa. Following Crough (1975), we considered the lithosphere as a thin plate whose thickness increases with age up to an age of 80 m.y., followed by a progressively reduced rate of thickening until it reaches an equilibrium thickness. Since the mechanical properties of the plate depend on its thickness, we studied the time evolution of the lithosphere by observing how it deforms when loaded by seamounts or ridges chosen at several points along its evolutionary path.

To account for the geoid signals observed so far, two models were considered: the thin-elastic-plate model and the Airy model (see, for example, McKenzie and Bowin, 1976). The thin-elastic-plate model applies when a load was developed on a thin plate of finite thickness that subsequently deformed. The magnitude and wavelength of the deformed area depend mostly on the flexural rigidity, which itself is proportional to the cube of the lithospheric thickness. The correlation function between the bathymetry and the geoid height determines the local value of the flexural rigidity. The first step in our procedure was to calculate theoretical correlation functions or admittances in wavenumber space for a variable flexural rigidity. Then we Fourier-transformed these functions in normal space, convolved them with the bathymetry reconstructed along the subsatellite positions, and obtained a theoretical geoid profile for comparison with the observed geoid heights (see, for example, Figures 1 through 4).

The Airy-type models apply when the load was created simultaneously with the lithosphere (or on a zero-thickness lithosphere) and developed light roots in order to establish local or regional isostatic equilibrium. The correlation function is different in this model (see Figure 5), but the procedure is the same as in the case of the thin elastic plate.

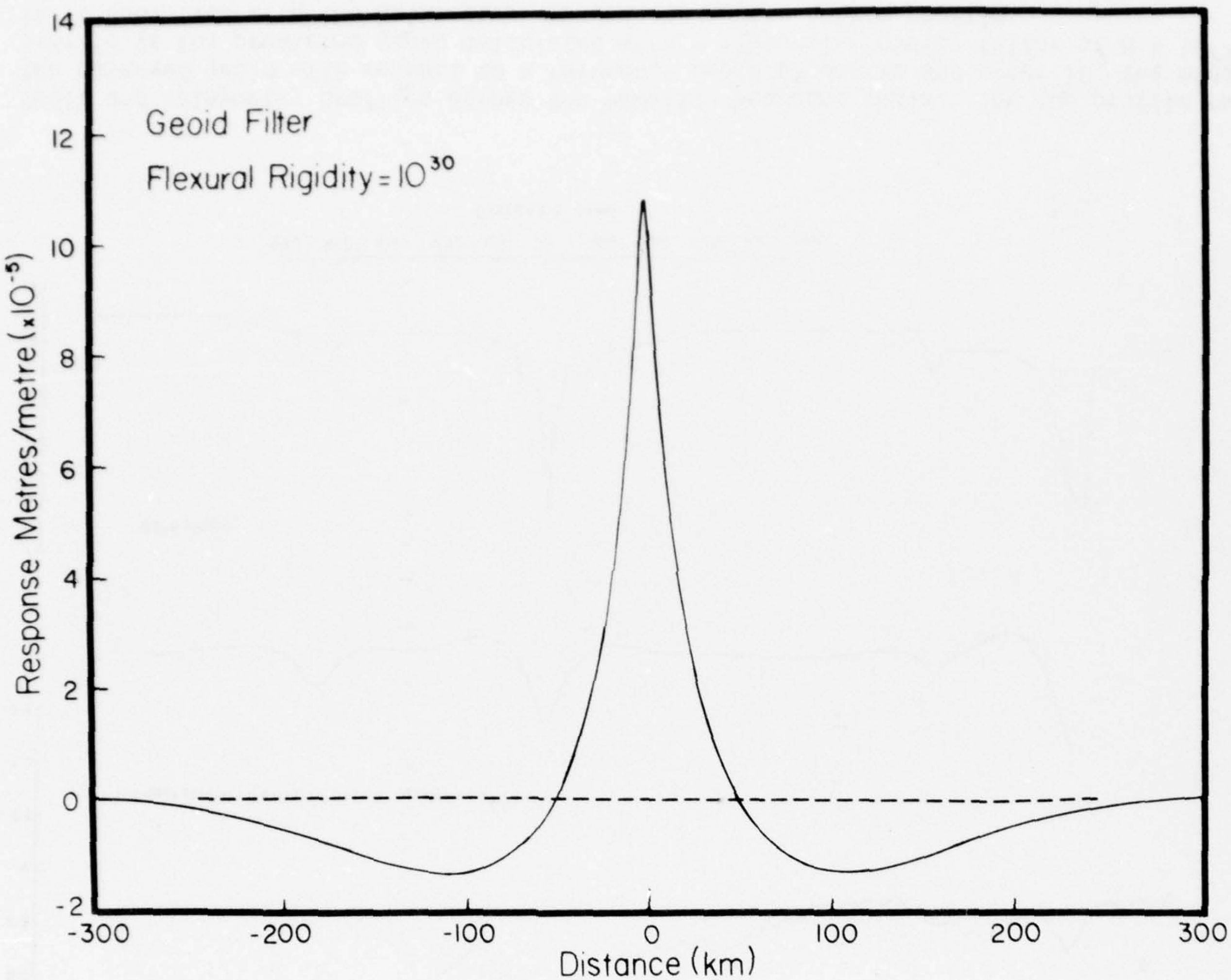

Figure 1. Geoid filter calculated by using a thin-elastic-plate model and a flexural-rigidity value of 10^{30} dyne-cm.

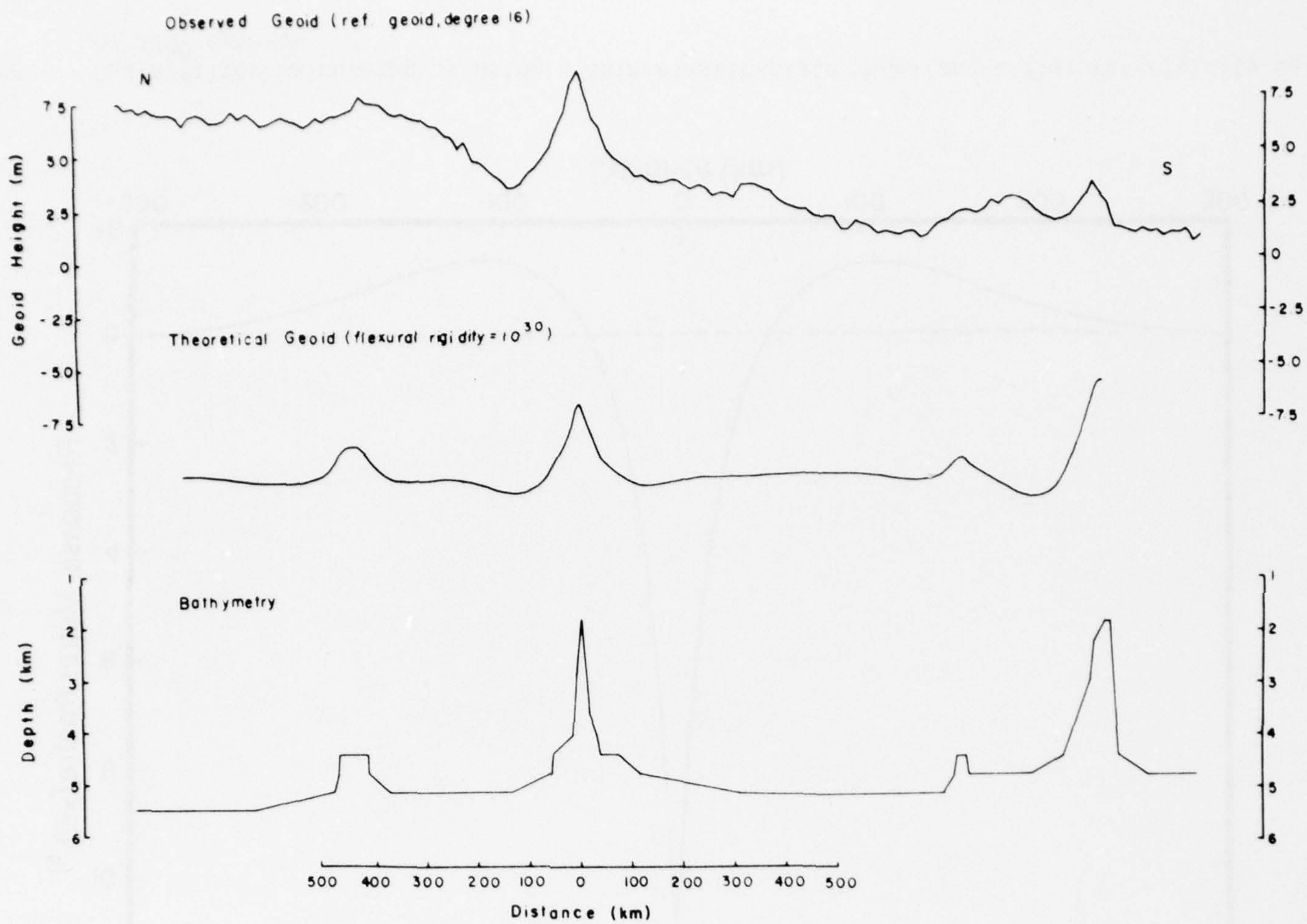

Figure 2. Geoid and bathymetry profiles across the Hawaiian Seamount chain. The top profile represents the observed geoid with respect to a reference geoid of degree and order 16; the middle profile is the predicted geoid calculated with a flexural-rigidity filter of 8×10^{29} dyne-cm; it is convolved with the bathymetry represented on the bottom profile.

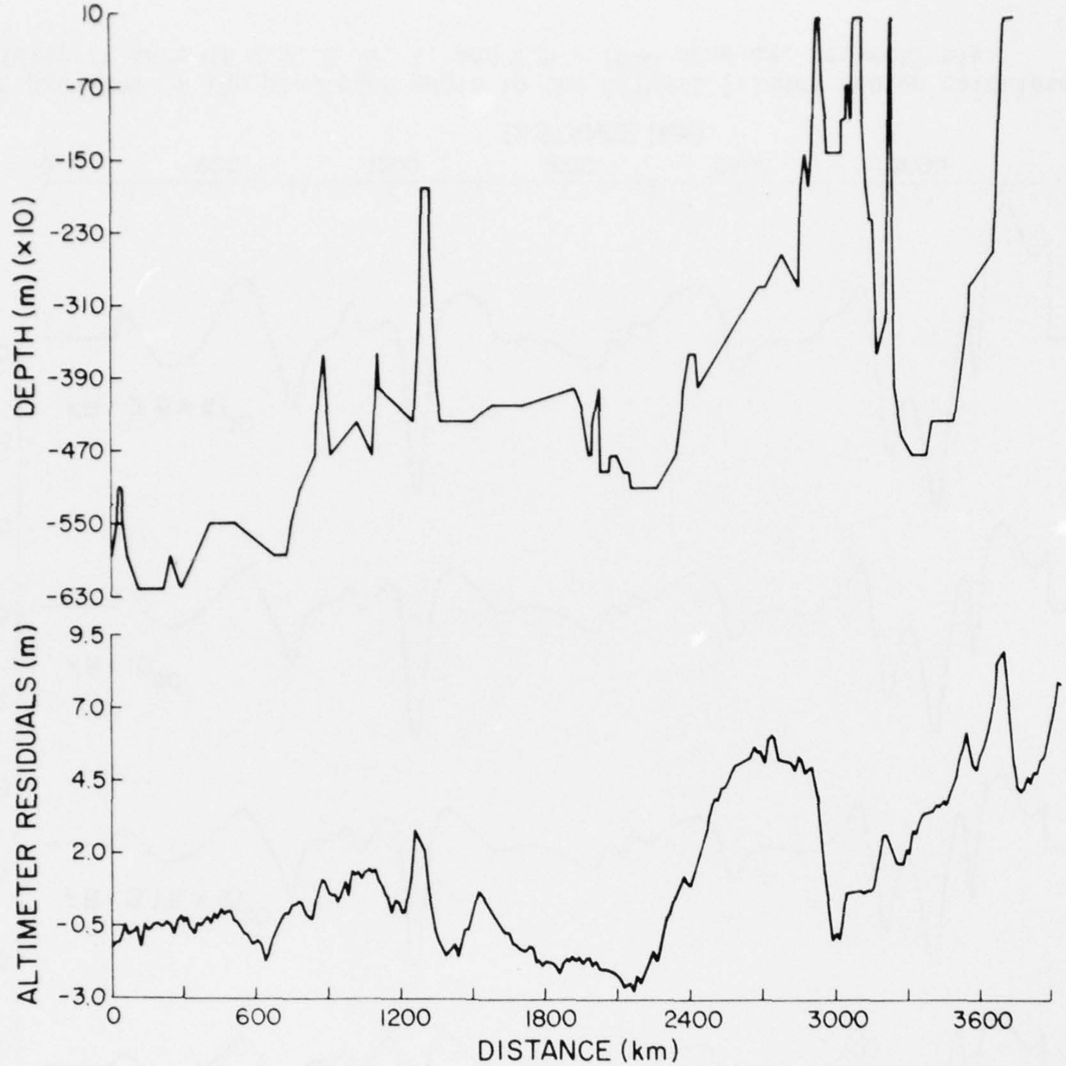

Figure 3. Bathymetry (top) and observed geoid (bottom) in the Gilbert Islands region; the bottom profile represents a reference geoid of degree and order 16.

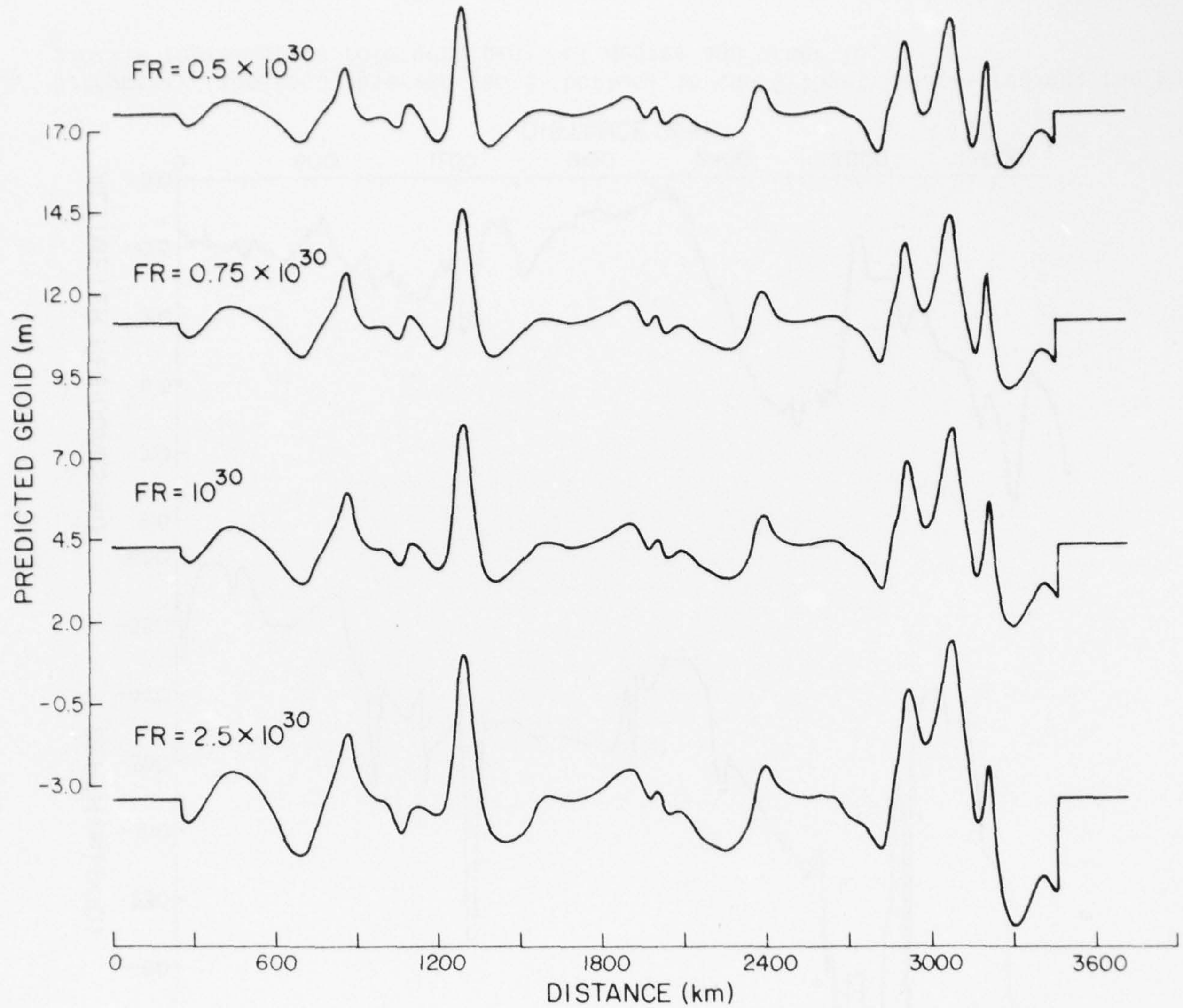

Figure 4. Four profiles of the predicted geoid in the Gilbert Islands region calculated with flexural-rigidity filters of 0.5, 0.75, 1, and 2.5 × 10^{30} dyne-cm, respectively.

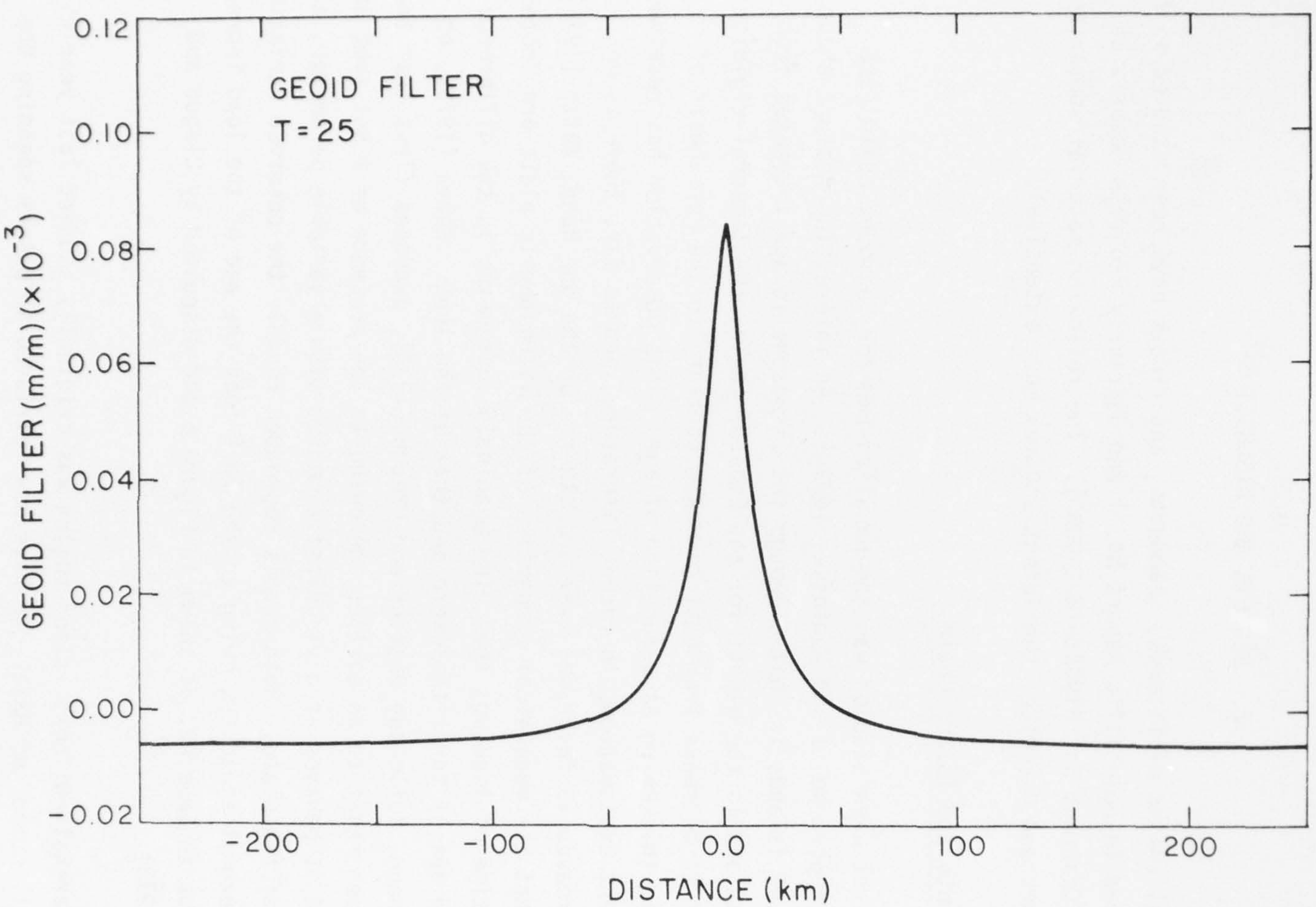

Figure 5. Geoid filter calculated by using an Airy-type model of isostatic compensation and a value of crustal thickness T of 25 km.

2. RESULTS AND DISCUSSION

Several chains of islands, seamounts, and ridges have been studied so far and described in Scientific Report No. 1 and Quarterly Progress Reports No. 1 through 6 (Contract No. F19628-78-C-0003). The following material summarizes the past work and describes the latest studies more extensively.

2.1 Seamounts and Island Chains

The first area studied was the Hawaiian-Emperor Seamount chain (see Scientific Report No. 1 and Roufosse, 1979a). An interesting feature about that chain of islands is that although the lithospheric age increases from east to west and is the oldest for the Emperor chain, the flexural-rigidity value tends to decrease from east to west, contrary to the hypothesis of lithospheric thickening as a function of age. This observation has received two different explanations in recent literature, and so far, there is no objective reason to favor one over the other. On the one hand, Watts (1978) proposes that the mechanical properties of the lithospheric plate are frozen in at the time of loading; thus, the meaningful parameter is the difference between the age of the lithosphere and that of the load. Jones (1979), on the other hand, following Detrick and Crough (1978), proposes first that the area has been reset to an earlier age owing to the presence of a hot spot and second that it behaves as a visoelastic medium with a variable parameter, the thickness of the plate. Both models reproduce roughly the observed variations for the flexural rigidity, owing to the fact that the age of the load increases from Kilauea to Emperor, as shown in Figure 6 and discussed by Clague and Jarrard (1973).

The Marshall-Gilbert Island region was originally studied last year with a very small number of data. We have now retrieved 40 passes spanning the whole length of the chain. The age of the lithosphere, derived from magnetic

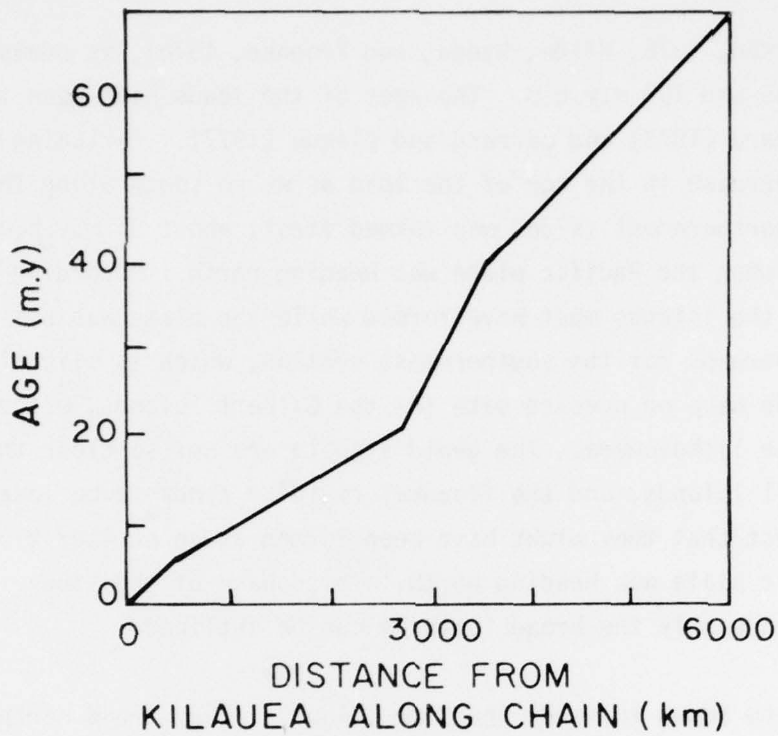

Figure 6. Plot of island or seamount age as a function of distance from Kilauea along the Hawaiian-Emperor Seamount chain.

lineations (Larson, 1976; Hilde, Uyeda, and Kroenke, 1976), is Jurassic and thus between 135 and 190 m.y.b.p. The ages of the loads have been taken from Clague and Jarrard (1973) and Jarrard and Clague (1977). Excluding Mejit, we observe a decrease in the age of the load as we go south along the Marshall Islands. The northernmost island was formed first, about 55 m.y.b.p., and thus at a time when the Pacific plate was heading north. According to our study, most of the islands must have formed while the plate was still heading north, except perhaps for the southernmost section, which is slightly bent to the east. We have no precise date for the Gilbert Islands, either for the loads or for the lithosphere. The geoid signals are not so clear there as for the Marshall Islands, and the flexural rigidity tends to be lower. We therefore suggest that they might have been formed at an earlier time, again when the Pacific plate was heading north. This phase of the study is not complete, and thus only the broad features can be outlined.

We have also begun to study the Line Islands. They trend northwest to southeast below the Hawaiian Seamount chain and are more or less parallel to the Emperor Seamount chain. The geoid signal there is broad and ill-defined. A few ages for the loads are known with certainty; they are of the order of 80^{+} m.y. For a few other loads, a minimum age is known, of the order of 45^{+} m.y. All these features represent much older loads than do the nearby Hawaiian Seamounts, although they lie on sections of the lithosphere that are roughly the same age, Cretaceous. Therefore, they must have been formed on young lithosphere when the Pacific plate was moving north. In addition, they are characterized by small flexural-rigidity values, of the order of 2.5×10^{29} dyne-cm. Following Morgan (1971, 1972a,b), we thus believe that the three island chains studied were produced by plate motion over convective plumes extending from near the core-mantle interface to the base of the lithosphere. Morgan hypothesized that a total of three hot spots were responsible for the formation of these chains, which are currently located at Hawaii, McDonald Seamount, and the intersection of the East Pacific Rise with the Sala y Gomez Ridge.

In our investigation of the Crozet, Kerguelen, and Heard Islands in the Indian Ocean (see Scientific Report No. 1), we found that Crozet fits the thin-elastic-plate model perfectly while Kerguelen does not. We believe that the Airy model will offer a much better description of this region, and we intend to resume our collaboration with Dr. A. Cazenave from the Centre National des Etudes Spatiales in Toulouse in order to examine that possibility.

2.2 Walvis Ridge

Another phase of our work was an examination of the Walvis Ridge in the South Atlantic Ocean. The Walvis Ridge is aseismic and is made up of three main segments:

1) An eastern segment, extending continuously from the African margin to longitude 6°E and trending east–northeast to west–southwest. It is approximately 600 km long and 100 to 200 km wide.

2) A central segment, trending north–south. This segment is lower and narrower than the eastern segment and is approximately 500 km long.

3) A western segment, made up of individual seamounts and divided into two branches, a sharp and elevated southern branch and a less marked northern branch. It extends to the Mid-Atlantic Ridge in the vicinity of Tristan da Cunha and Gough Islands.

Concerning the origin of the Walvis Ridge, there are two main hypotheses. The first is that it formed synchronously with the opening of the South Atlantic and resulted from hot spots (Morgan, 1971, 1972a,b; Le Pichon and Hayes, 1971; Francheteau and Le Pichon, 1972). The second is that it was created after the opening of the South Atlantic and is related to a major uplift (Ewing, Le Pichon, and Ewing, 1966; Maxwell and others, 1970). To distinguish between these two hypotheses, several investigators (Goslin, Mascle, Sibuet, and Hoskins, 1974; Goslin and Sibuet, 1975; Dingle and Simpson, 1976) have made use of all the information available for the eastern section of the ridge: bathymetry, seismic profiles, magnetic anomalies, age of the load, sedimentary distribution, morphology and constitution of the ridge, and gravity data. They all concluded that the easternmost section of the ridge was formed simultaneously with the lithosphere, on the ridge, by a mantle hot spot. Furthermore, it is probably controlled by lines of weakness in the lithosphere such as transform faults. By no means can it represent a load superimposed on the lithosphere; this is ruled out by the gravity anomalies that suggest compensating roots down to a depth of about 25 km.

If we observe the direction of the Walvis Ridge, it is incompatible with a fixed hot-spot origin. It has been postulated that after the eastern segment was formed, approximately 127 to 80 m.y.b.p., the South Atlantic opening pole shifted at about 80 m.y.b.p. (Le Pichon and Hayes, 1971). It is likely that the center of the volcanic activity, which was responsible for creating the central section of the Walvis Ridge, moved southward at that time. The hot spot then presumably moved to the location of Tristan da Cunha, where it created the western section of the ridge, which thus developed on older lithosphere. If that is true, a thin-elastic-plate model, similar to that used for the Hawaiian, Marshall-Gilbert, and Line Islands, should be best suited to describe the western section of the Walvis Ridge. We used geoid heights derived from the Geos 3 radar altimeter to investigate the structure of the Walvis Ridge and selected 16 satellite passes evenly spaced along the whole length of the ridge, as seen in Figure 7. We applied the Airy model with variable plate thickness and the thin-elastic-plate model with variable flexural rigidity to all these profiles. Eight of the profiles are presented in Figures 8 and 9. The eastern section of the ridge shows strong broad and asymmetrical signals with occasional dual structures, which account for the two separate ridges forming that section: the Valdivia Bank and the Frio Ridge. The central section reveals weaker and narrower signals, while the western section shows dual signals, a sharp and intense southern peak and a weak northern signal. The geoid heights thus faithfully reflect the bathymetry of the area.

In the eastern section of the Walvis Ridge, the thin-elastic-plate value for the flexural rigidity that best accounts for the intensity of the observed geoid is very large, of the order of 2.5×10^{30} dyne-cm. This model, however,

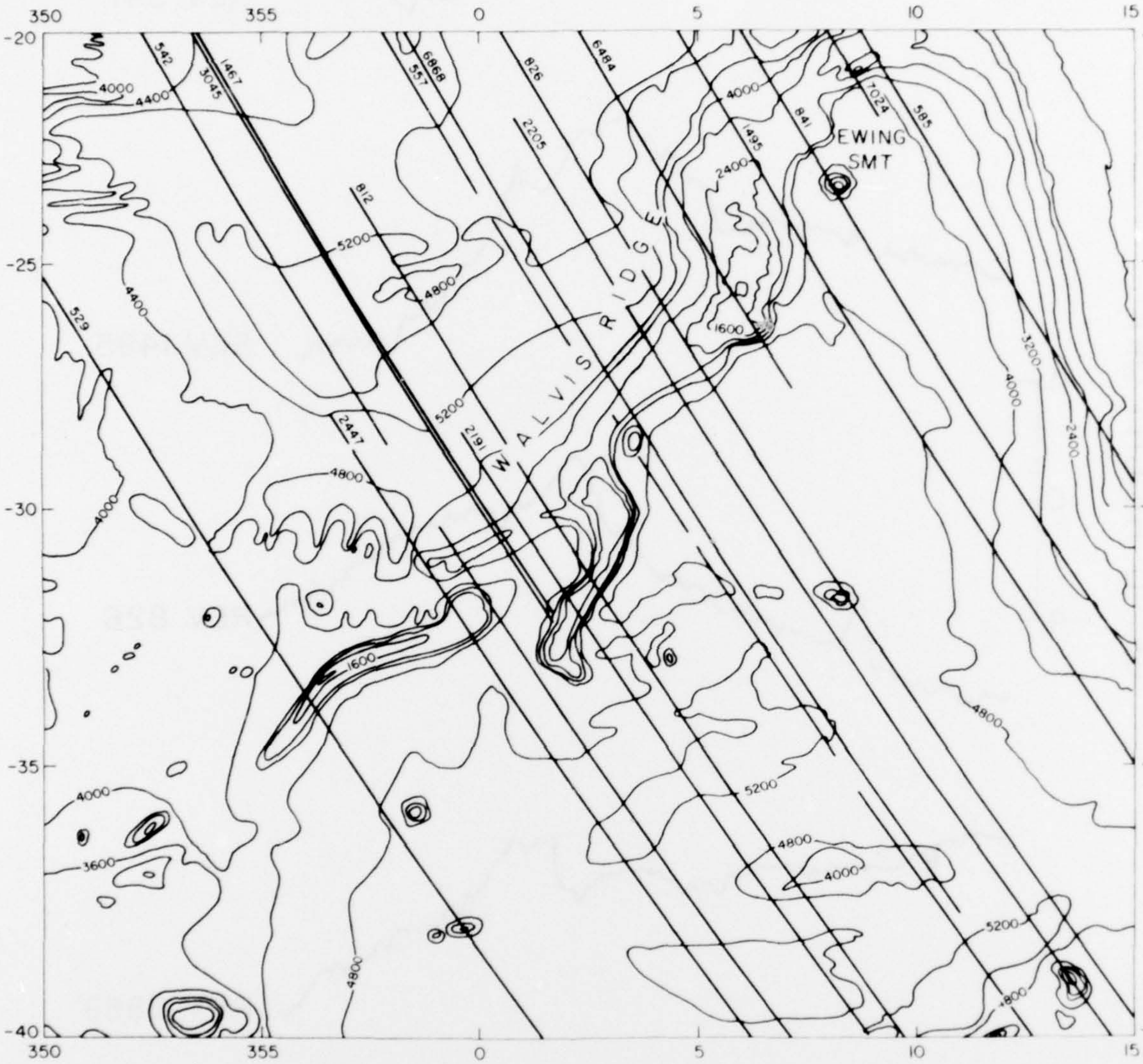

Figure 7. Bathymetry of the Walvis Ridge area and plot of the satellite passes selected over that region.

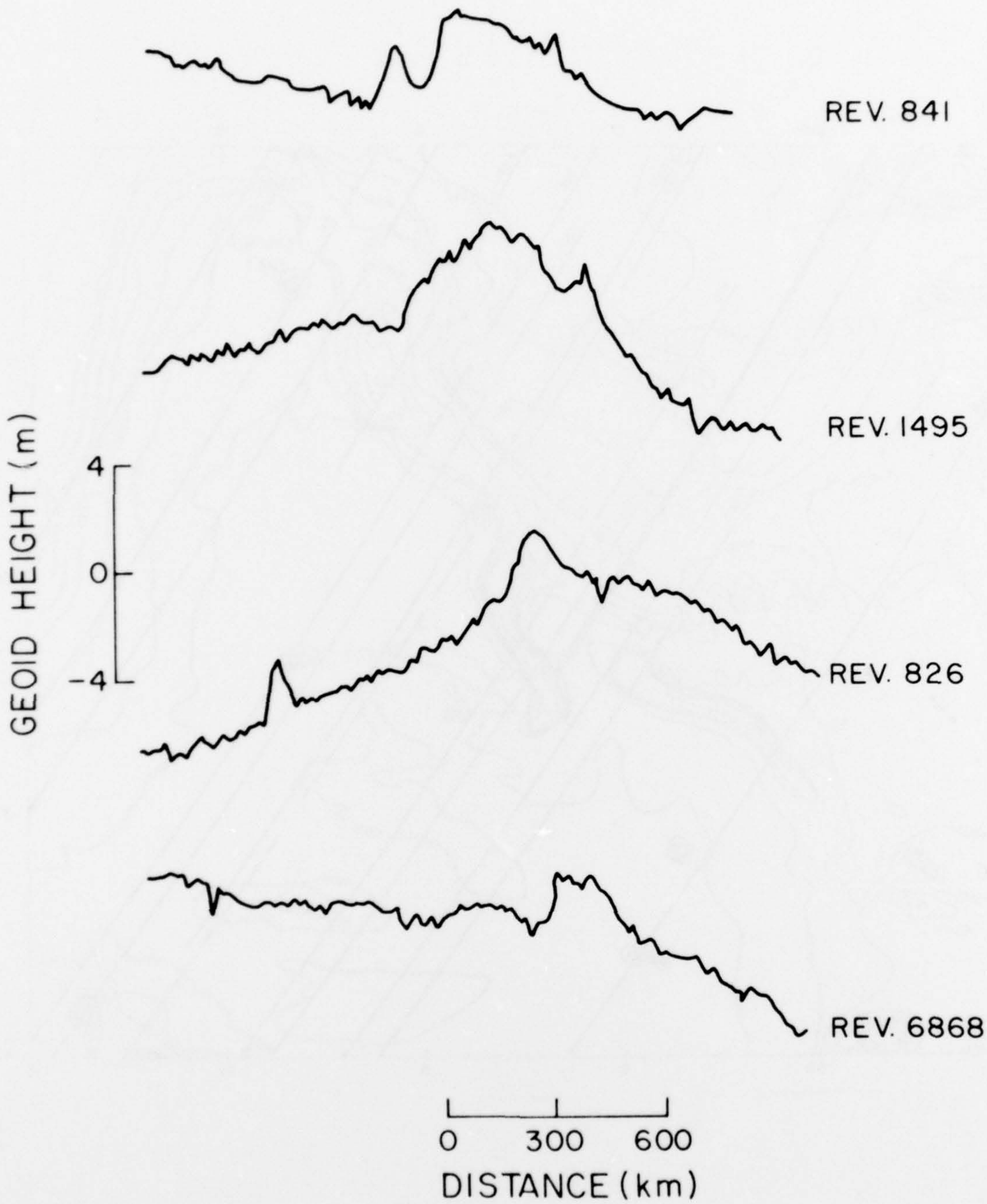

Figure 8. Four observed geoid profiles over the eastern and central sections of the Walvis Ridge, represented with respect to a reference geoid of degree and order 16.

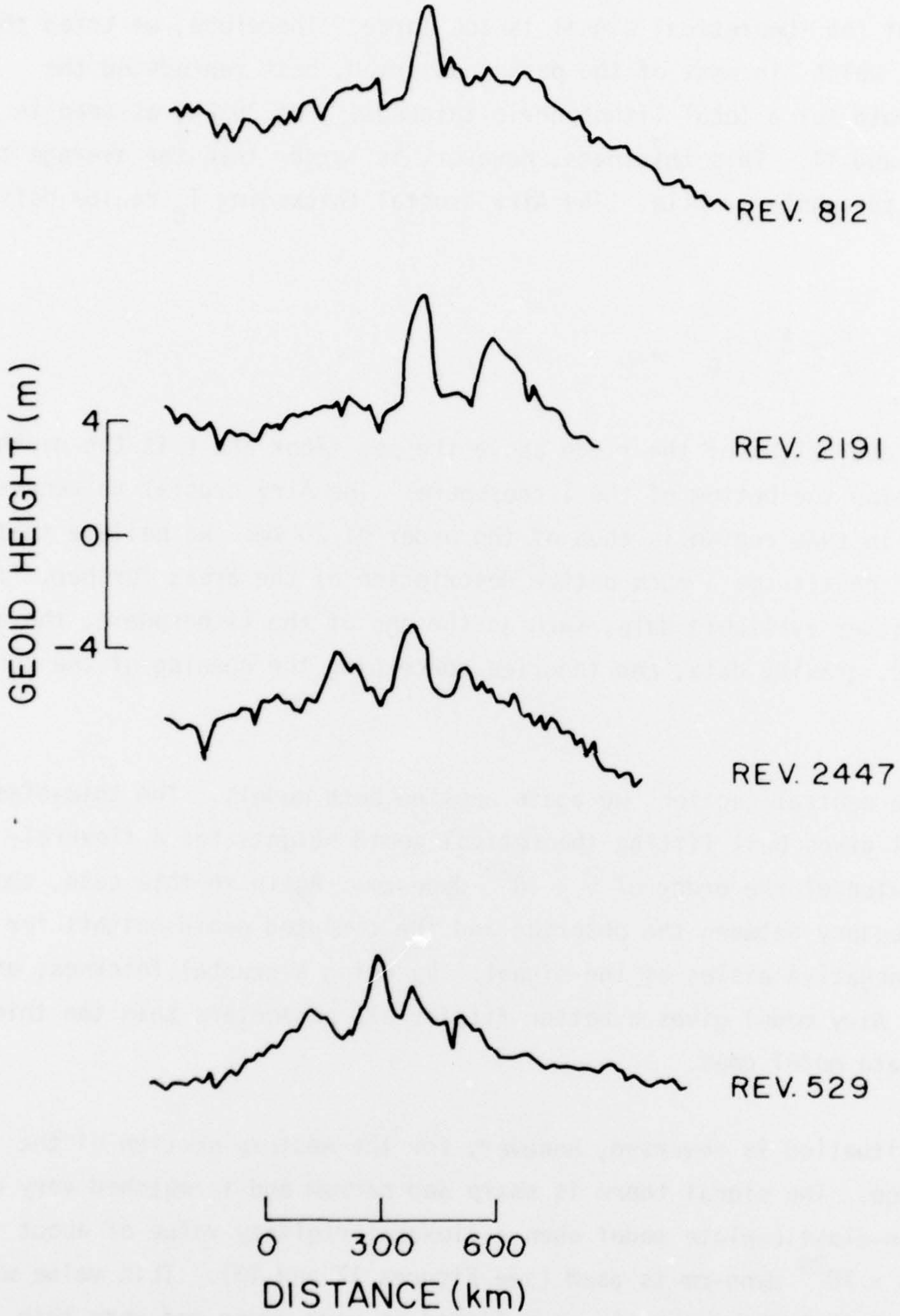

Figure 9. Four observed geoid profiles over the western section of the Walvis Ridge, represented with respect to a reference geoid of degree and order 16.

gives negative aisles that are not apparent in the observed geoid; moreover, the width of the theoretical signal is too large. Therefore, we tried the Airy model, which, in most of the passes observed, best reproduced the observed geoid for a local lithospheric thickness T of 25 km, as seen in Figures 10 and 11. This thickness, however, is larger than the average thickness along the whole profile. The Airy crustal thickening T_c can be defined by

$$T = \frac{h}{2} + \frac{t}{2} + T_c \quad ,$$

where h is the height of the ridge above the sea floor and t is the depth of the root below the bottom of the lithosphere. The Airy crustal thickness determined in that region is thus of the order of 20 km. We believe that the Airy model constitutes a much better description of the area; further, it fits with other available data, such as the age of the lithosphere, the age of the load, gravity data, and theories concerning the opening of the South Atlantic.

In the central section, we again applied both models. The thin-elastic-plate model gives best fitting theoretical geoid heights for a flexural-rigidity value of the order of 5×10^{29} dyne-cm. Again in this case, there is a discrepancy between the observed and the computed geoid heights for the width and negative aisles of the signal. By using a crustal thickness of 25 km, the Airy model gives a better fit for all parameters than the thin-elastic-plate model does.

The situation is reversed, however, for the western section of the Walvis Ridge. The signal there is sharp and narrow and is matched very well by the thin-elastic-plate model when a flexural-rigidity value of about 0.8 to 1.0×10^{29} dyne-cm is used (see Figures 12 and 13). This value would thus suggest that the seamounts were formed on very young and very thin lithosphere, of the order of 8 to 10 km thick. These values for the lithospheric thickness are similar to but larger than those found by Detrick and

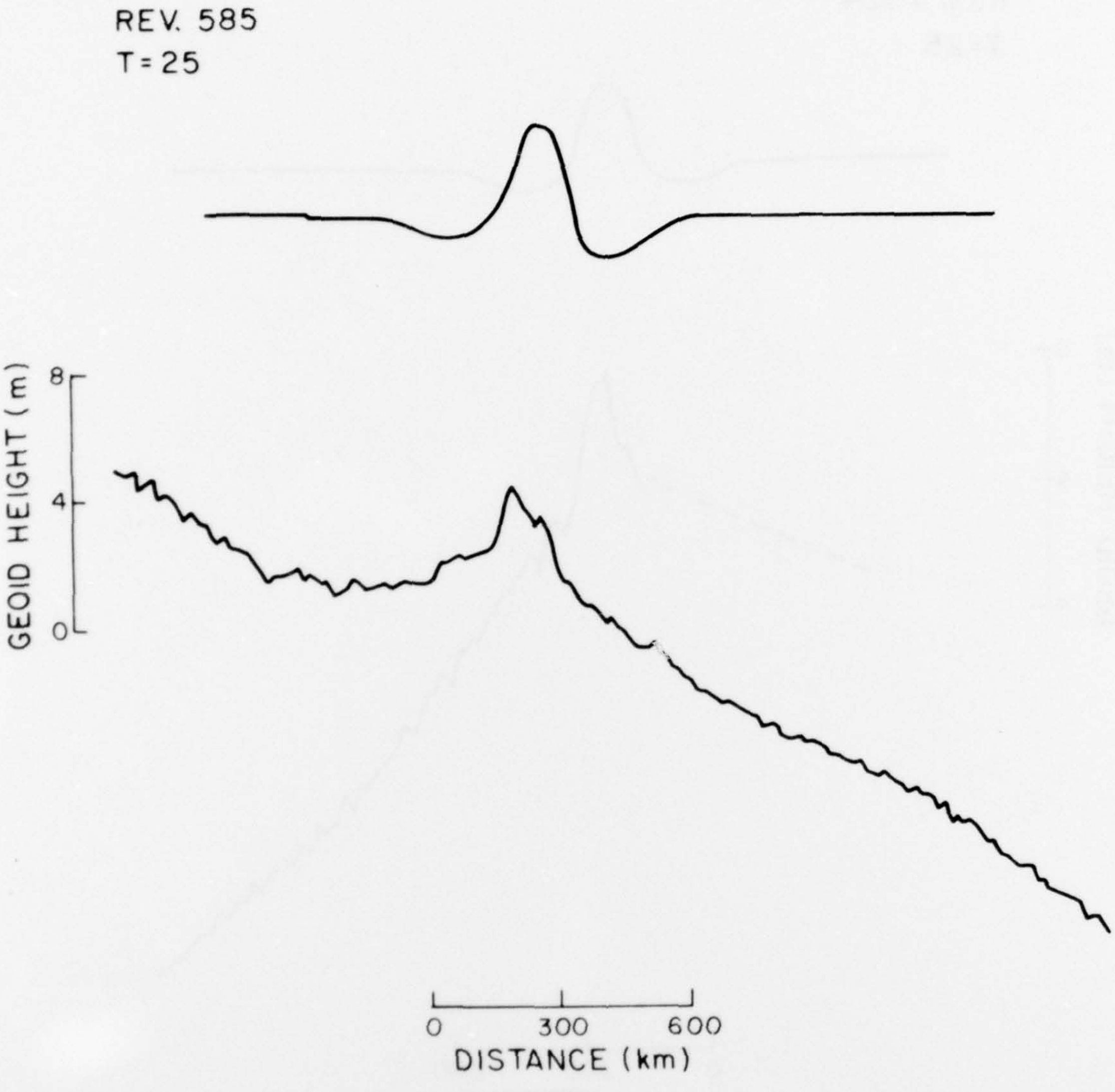

Figure 10. Predicted (top) and observed (bottom) geoid height for satellite revolution number 585 over Walvis Ridge. The top profile uses the Airy-type model with a crustal thickness of 25 km. The observed geoid is given with respect to a reference geoid of degree and order 16.

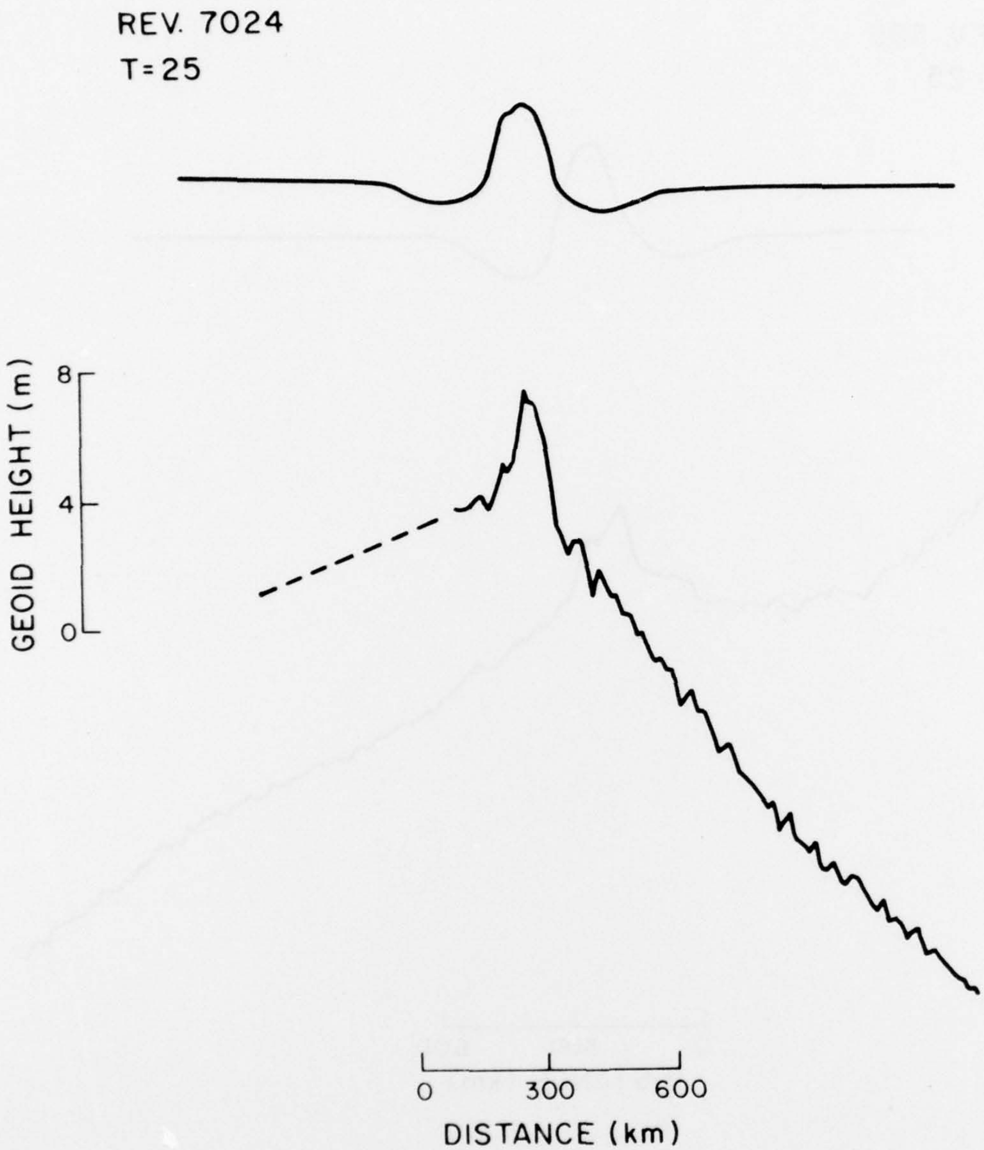

Figure 11. Same as Figure 10 for satellite revolution number 7024.

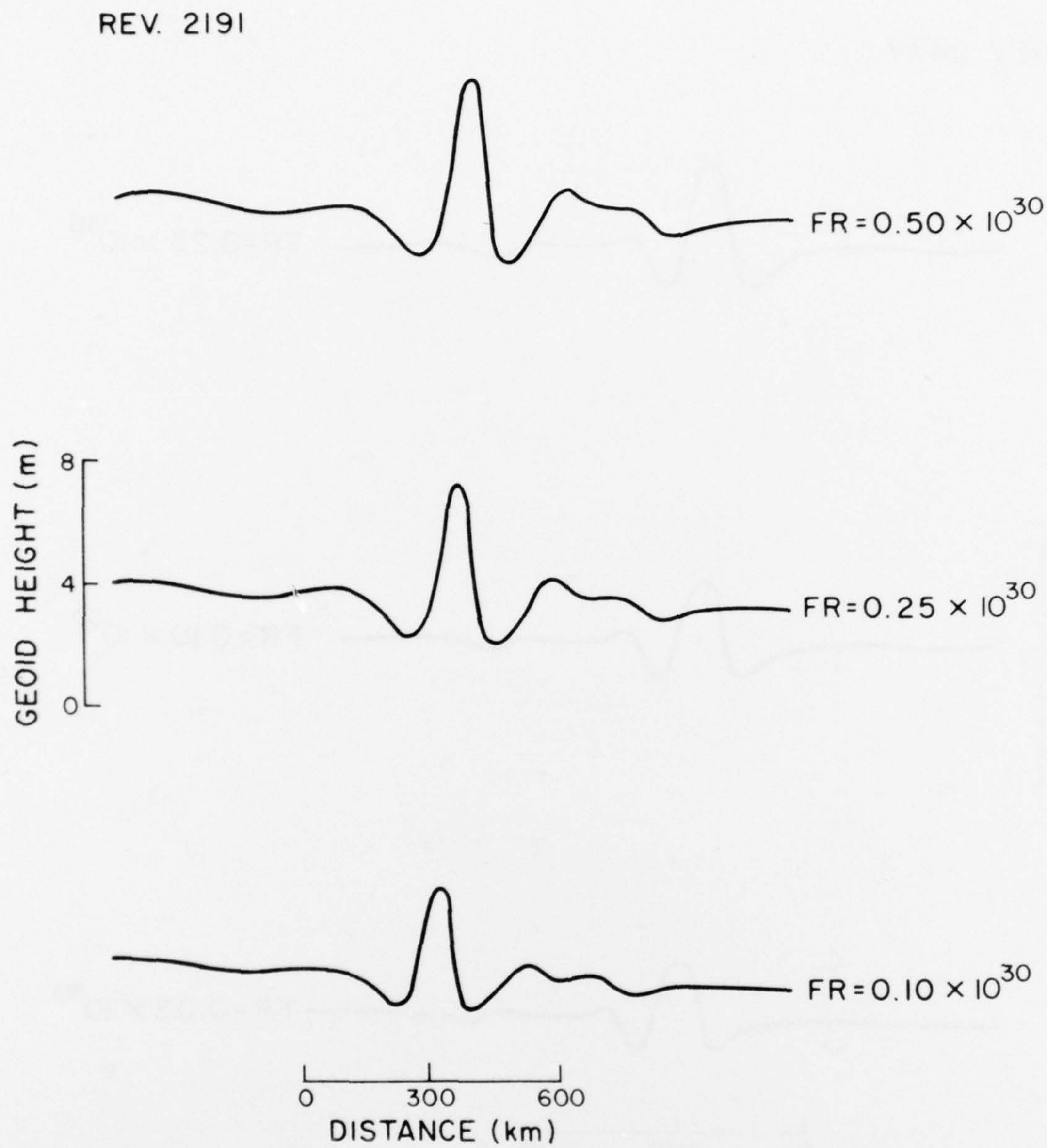

Figure 12. Three predicted geoid heights for satellite revolution number 2191 over Walvis Ridge, calculated from the thin-elastic-plate model with flexural-rigidity values of 0.50, 0.25, and 0.10 × 10^{30} dyne-cm.

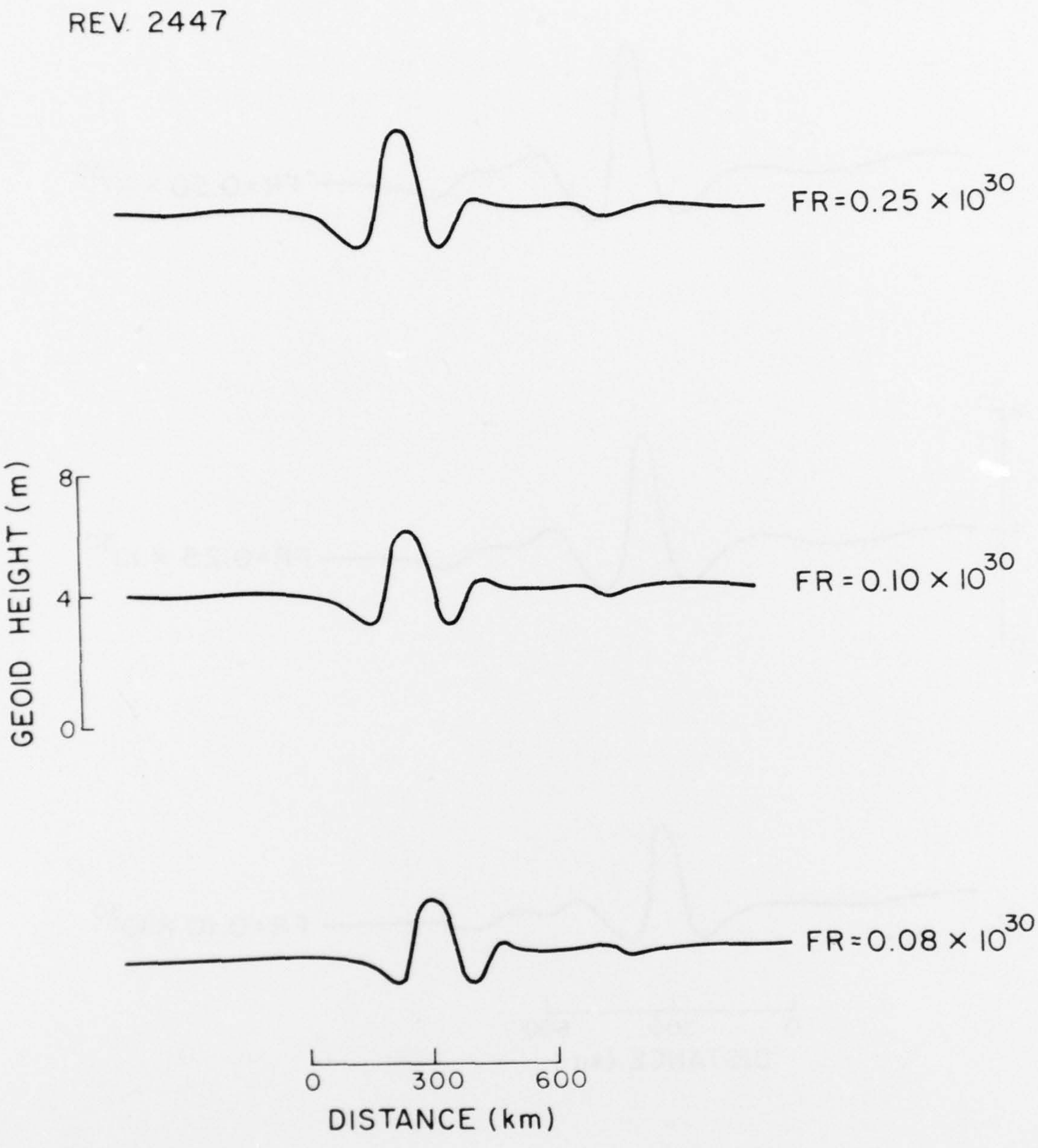

Figure 13. Same as Figure 12 for satellite revolution number 2447 and for flexural-rigidity values of 0.25, 0.10, and 0.08 × 10^{30} dyne-cm.

Watts (1979) in the same area in their correlation of surface ship gravity data and bathymetry data. The slight discrepancy can be easily accounted for by the nature of the bathymetry used in our study. Our bathymetry profiles were reconstructed along the subsatellite positions from the Uchupi bathymetric charts, which have 400-m contours; thus, we could overestimate the depth of the bottom floor and underestimate the ridge height by as much as 399 m. We performed the calculations a second time using visual interpolation for points between bathymetry contours. This lowered the flexural rigidity to 6×10^{28} dyne-cm, in perfect agreement with other researchers.

So far, we have studied a large variety of bathymetric features spanning different lithospheric ages and conditions of creation and evolution. The two main factors that seem to influence the geoid heights are the conditions of creation (e.g., hot spot and uplift) on the one hand and the age of the lithosphere at the time of loading (e.g., position with respect to the ridge axis) on the other hand. The latter point requires further investigation, however, because it seems that the actual lithospheric age should be present in the geoid signal. In future research, we hope to resolve that discrepancy by using both Geos 3 and Seasat radar altimeter data acquired over several other bathymetric features.

2.3 Continental Lithosphere

In this two-year effort, the first year dealt mostly with the interpretation of the short-wavelength features in the earth's gravity field over continental regions. This work was discussed extensively in Scientific Report No. 1 and in Roufosse (1979b); it is summarized here. Regression lines between the short-wavelength features in the gravity and topography fields were obtained in $5° \times 5°$ squares for continental regions, together with the average age of the basement rocks for each square. Plotting the distribution of the slopes of the regression lines as a function of age of the regions, we found that the slopes increased with increasing age. This observation was compared with models for the continental lithosphere (Crough and Thompson, 1976b). Starting from these models, it is possible to evaluate the free-air anomalies associated with columns of material 400 km deep composed of appropriate proportions of crust, lithosphere, and mantle and compare these anomalies with the topography to determine a theoretical linear-regression slope. We found qualitative agreement between the observed and the calculated slopes. This work is further compared with seismic data derived by Sengupta (1975), which shows an increase in P-wave velocity anomalies with increasing age.

2.4 Conclusions

In the course of this study, we became aware of shortcomings in the data set utilized. Over continental regions, the surface gravity data are very abundant in certain areas, such as the northern United States, but are either nonexistent or are the result of predictions in other areas. Over oceanic regions, they are still very scarce. We thus decided to utilize a combination of surface ship gravity data, Geos 3 radar altimeter data, and Apollo range-rate residuals to perform an extensive study of the Indian Ocean. This work is in progress, for which we are collaborating with Dr. P. McKenzie from Cambridge University, U.K., Dr. B. Parsons from Massachusetts Institute of Technology, and Dr. A. Watts from Lamont Doherty Geological Observatory. Such a thorough study is a vast undertaking and cannot be achieved easily by a single researcher; we believe that our collaboration will lead to significant progress on understanding convection in the mantle. The correlation function between the long-wavelength features in the gravity and those in the bathymetry fields will be studied as a function of wavelength; the shape of the function is very sensitive both to the depth of the convection cells and to the viscosity variations within these cells (McKenzie, 1977).

In conclusion, we have tried in this work to extract maximum information from the Geos 3 altimetry data in both the long- and the short-wavelength portions of the spectrum. We have made significant progress so far, but we have not completely exploited the wealth of information contained in that data set. Research in the coming years will focus on continued interpretation of this wealth of Geos 3 data, together with data from Seasat.

3. REFERENCES

Clague, D. A., and Jarrard, R. D., 1973. Tertiary Pacific plate motion deduced from the Hawaiian-Emperor chain. Geol. Soc. Amer. Bull., vol. 84, pp. 1135-1154.

Crough, S. T., 1975. Thermal model of oceanic lithosphere. Nature, vol. 256, pp. 388-390.

Crough, S. T., and Thompson, G. A., 1976a. Numerical and approximate solutions for lithospheric thickening and thinning. Earth and Planet. Sci. Lett., vol. 31, pp. 397-402.

Crough, S. T., and Thompson, G. A., 1976b. Thermal model of continental lithosphere. Journ. Geophys. Res., vol. 81, pp. 4857-4862.

Detrick, R. S., and Crough, S. T., 1978. Island subsidence, hot spots and lithospheric thinning. Journ. Geophys. Res., vol. 83, pp. 1236-1244.

Detrick, R. S., and Watts, A. B., 1979. An analysis of isostasy in the world's oceans: Part 3 - Aseismic ridges. Journ. Geophys. Res., in press.

Dingle, R. V., and Simpson, E. S. W., 1976. The Walvis Ridge: A review. In Geodynamics: Progress and Prospects, ed. by C. L. Drake, American Geophysical Union, Washington, D.C., pp. 160-176.

Ewing, M., Le Pichon, X., and Ewing, J., 1966. Crustal structure of the mid-ocean ridges: 4-sediment distribution in the south Atlantic Ocean and the Cenozoic history of the Mid-Atlantic Ridge. Journ. Geophys. Res., vol. 71, pp. 1611-1635.

Francheteau, J., and Le Pichon, X., 1972. Marginal fracture zone as structural framework of continental margins in the South Atlantic Ocean. Amer. Assoc. Petroleum Geol. Bull., vol. 56, pp. 991-1007.

Goslin, J., Mascle, J., Sibuet, J. C., and Hoskins, H., 1974. Geophysical study of the easternmost Walvis Ridge, South Atlantic: Morphology and shallow structure. Geol. Soc. Amer. Bull., vol. 85, pp. 619-632.

Goslin, J., and Sibuet, J. C., 1975. Geophysical study of the easternmost Walvis Ridge, South Atlantic: Deep structure. Geol. Soc. Amer. Bull., vol. 86, pp. 1713-1724.

Hilde, T. W. C., Uyeda, S., and Kroenke, L., 1976. Tectonic history of the Western Pacific. In Geodynamics: Progress and Prospects, ed. by C. L. Drake, American Geophysical Union, Washington, D.C., pp. 1-15.

Jarrard, R. D., and Clague, D. A., 1977. Implications of Pacific island and seamount ages for the origin of volcanic chains. Rev. Geophys. Space Phys., vol. 15, pp. 57-76.

Jones, G. M., 1979. Visco-elastic flexure of oceanic lithosphere. Submitted to Geophys. Journ. Roy. Astron. Soc.

Larson, R. L., 1976. Late Jurassic and early Cretaceous evolution of the Western Central Pacific Ocean. Journ. Geomagn. Geomech., vol. 28, pp. 219-236.

Le Pichon, X., and Hayes, D. E., 1971. Marginal offsets, fracture zones and the early opening of the South Atlantic. Journ. Geophys. Res., vol. 76, pp. 6283-6296.

Maxwell, A. E., Von Herzen, R. P., Hsü, K. J., Andrews, J. E., Saito, T., Percival, S. F., Milow, E. D., Jr., and Boyce, R. E., 1970. Deep sea drilling in the South Atlantic. Science, vol. 168, pp. 1047-1059.

McKenzie, D. P., 1977. Surface deformation, gravity anomalies and convection. Geophys. Journ. Roy. Astron. Soc., vol. 48, pp. 211-238.

McKenzie, D. P., and Bowin, C., 1976. The relationship between bathymetry and gravity in the Atlantic Ocean. Journ. Geophys. Res., vol. 81, pp. 1903-1915.

Morgan, W. J., 1971. Convection plumes in the lower mantle. Nature, vol. 230, pp. 42-43.

Morgan, W. J., 1972a. Deep mantle convection plumes and plate motions. Amer. Assoc. Petroleum Geol. Bull., vol. 56, pp. 203-213.

Morgan, W. J., 1972b. Plate motions and deep mantle convection. Geol. Soc. Amer. Mem., vol. 132, pp. 7-22.

Roufosse, M., 1979a. Interpretation of altimeter data. In An International Symposium on the Applications of Geodesy to Geodynamics, Proceedings of the 9th GEOP Conference, Ohio State Univ., Dept. Geod. Sci., Rep. No. 280, pp. 261-266.

Roufosse, M., 1979b. Correlations of topographic heights and free air anomalies and their implication on lithospheric models. Tectonophys., in press.

Sengupta, M. K., 1975. The structure of the earth's mantle from body wave observations. Ph.D. Thesis, Massachusetts Institute of Technology.

Walcott, R. I., 1976. Lithospheric flexure, analysis of gravity and the propagation of seamount chains. In The Geophysics of the Pacific Ocean Basin and Its Margin, ed. by G. H. Sutton, M. H. Manghnani, and R. Moberly, Amer. Geophys. Union Mono. 19, Washington, D.C., pp. 431-438.

Watts, A. B., 1976. Gravity and bathymetry in the Central Pacific Ocean. Journ. Geophys. Res., vol. 81, pp. 1533-1553.

Watts, A. B., 1978. An analysis of isostasy in the world's oceans: 1, Hawaiian-Emperor Seamount chain. Journ. Geophys. Res., vol. 83, pp. 5989-6004.

Watts, A. B., and Cochran, J. R., 1974. Gravity anomalies and flexure of the lithosphere along the Hawaiian-Emperor Seamount chain. Geophys. Journ. Roy. Astron. Soc., vol. 38, pp. 119-141.